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# NUCLEON RESONANCES AND NUCLEI
## - Experimental Aspects -

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# NUCLEON RESONANCES AND NUCLEI

## - Experimental Aspects -

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Abstract

An overview of the experimental status of nucleon resonance transition form factors is given. Recent photo- and electroproduction experiments from nuclei in the resonance region are discussed, and prospects for measurements at future CW electron accelerators are briefly addressed.

## INTRODUCTION

The title of my talk suggests a rather general coverage of the subject of nucleon resonances in nuclei. What the experimental aspects concern, however, is the $\Delta(1232)$, the only resonance that has been of relevance in studies involving nuclei. This, of course, is given by the limitation in energy of accelerators which are presently being used in nuclear physics experiments.

In this talk, I want to focus on recent experiments performed at electron machines with photon or electron beams, respectively. This is primarily motivated by the bright future that one may predict for nucleon resonance studies at the powerful CW electron machines in the several-GeV region, which are presently being planned and under construction at various places in the world.

With the 4-GeV CEBAF accelerator, for example, many of the higher mass resonances can be studied over a large $Q^2$ range. At these energies nucleon resonances will also play an important role in many electro- and photo-induced nuclear reactions. Detailed knowledge of the electromagnetic properties of free nucleon resonances is necessary when studying their properties in nuclei. It may therefore be appropriate to begin with a brief review of our experimental knowledge of electroexcitation of free nucleon resonances.

## I. ELECTROMAGNETIC EXCITATION OF FREE NUCLEONS

The primary motivation for studying the electromagnetic transition into excitated nucleon states ($N^* = N,\Delta$) is given by the possibility to obtain information on the photo-coupling amplitudes (PCA) of the $\gamma NN^*$ vertex.

Knowledge of the PCA and their $Q^2$ dependence is essential for testing microscopic models of the nucleon and of the photon-nucleon coupling, and provides us with details of the wavefunction of the excited state. In the context of dynamical quark models this is closely connected to the interaction of light quarks in confined systems. This interaction is generally conceived to be governed by the theory of strong interaction, QCD. At present, the connection between baryons and QCD is made via models which employ ingredients from QCD, e.g. the model developed by N. Isgur & G. Karl[1] which implements the one-gluon-exchange potential.

Besides attempts to understand the fundamental interaction at the quark-gluon level, measurements of the PCA and the transition form factors are essential for intermediate energy nuclear physics as they provide the empirical basis for a study of nucleon resonance excitation and interaction in nuclei. Clearly, only the precise knowledge of the "elementary" reaction will enable us to search for possible modification of the resonance excitation in the nuclear medium.

## I. Electroproduction of Pseudoscalar Mesons

For an excited state with given spin J and isospin I, the $\gamma NN^*$ vertex can be characterized by 3 photo-coupling amplitudes $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$ and $C_{1/2}(Q^2)$, where A and C refer to the transverse and longitudinal amplitudes, respectively. 1/2 and 3/2 are the total helicities in the initial $\gamma N$ system. Equivalently, electromagnetic multipoles $E_{l\pm}$, $M_{l\pm}$, $S_{l\pm}$ can be used, where l refers to the angular momentum of the final state and $J = l \pm 1/2$.

The shape of the inclusive cross section $ep \rightarrow eX$ at fixed $Q^2$ is shown in Fig. 1, where the best-known nucleon resonances below 2 GeV are indicated as well. The large number of states and their large width prevent a separation of individual resonances on the basis of inclusive measurements alone. Exclusive experiments are necessary to identify spin/parity and isospin of the intermediate state (Fig. 2). Many of these states have a large branching ratio into $\pi N$ or $\eta N$. These channels are particularly convenient to study because their hadronic vertices are well known from $\pi N$ elastic scattering.

The reaction $\gamma_v p \rightarrow p\eta$ selects final states with isospin $I = 1/2$ and provides a tag for the $S_{11}(1535)$ and $P_{11}(1710)$ resonances, both of which have a large branching ratio into the $p\eta$ channel. The cross section for $\eta$ production in the $S_{11}(1535)$ region shows an s-wave behavior and a clear resonant structure with little nonresonant background[2] (Fig. 3). The $A_{1/2}$ amplitude of the $S_{11}(1535)$ has been extracted, which exhibits a strikingly weak $Q^2$ dependence (Fig. 4). At $Q^2 = 3\ (\mathrm{GeV}/c)^2$ the amplitude has decreased by only a factor of $\simeq 2$ compared to its magnitude at $Q^2 = 0$. The longitudinal coupling was found to be small[3] : $\sigma_L/\sigma_T \simeq 0. - 0.2$ for $Q^2 = 0.3$ to $1.5\ (\mathrm{GeV}/c)^2$.

An intriguing aspect of the dominant resonant structure of the $p\eta$ channel and its slow fall-off with $Q^2$ is that it makes $\eta$ production a sensitive tool for probing nuclei with nucleon resonances (see III).

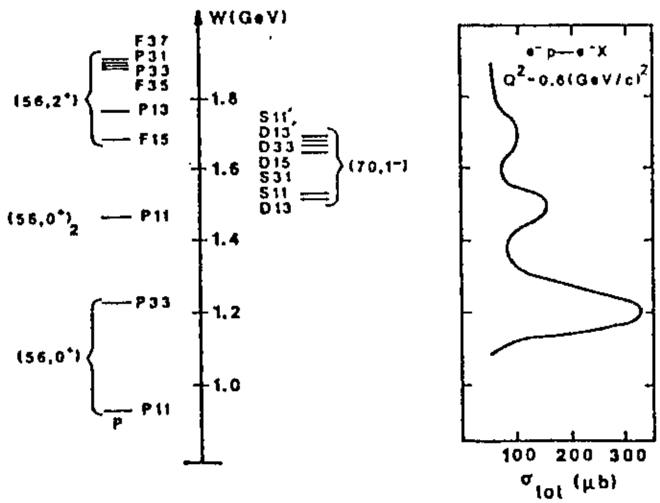



Fig. 1 Shape of the inclusive cross section p(e,e´)X at fixed $Q^2$, as a function of the invariant mass W(r.h.s.). The nucleon states with I = 1/2, 3/2 and strangeness 0 with masses below 2 GeV, together with their SU(6) assignments (l.h.s.).

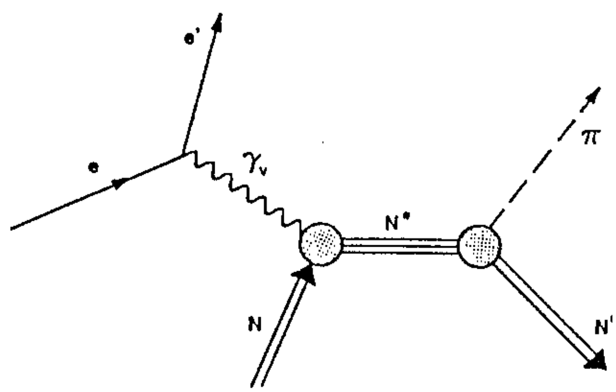



Fig. 2 Electroproduction of N * resonances and single pseudoscalar meson decay. The hadronic vertex is known from elastic πN scattering analysis. The electromagnetic vertex is described by 2 (J = 1/2) or 3 (J ≥ 3/2) transition form factors.

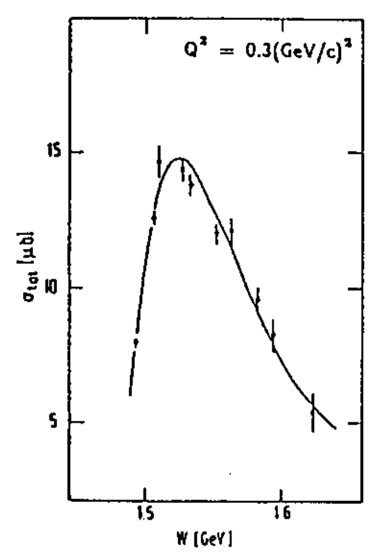
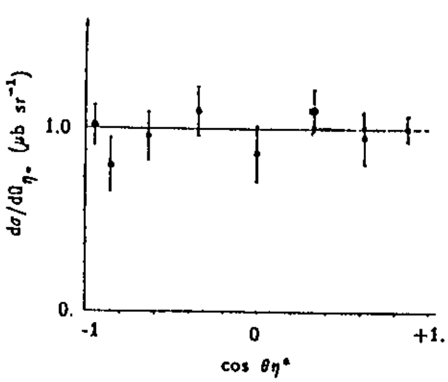



Fig. 3 Total cross section for $\eta$-electroproduction from protons at $Q^2$ = 0.3 $(GeV/c)^2$. The line represents a fit using a relativistic Breit-Wigner resonance with an s-wave threshold behavior (l.h.s.). Angular distribution of $\eta$ production at the resonance mass W = 1.535 GeV.



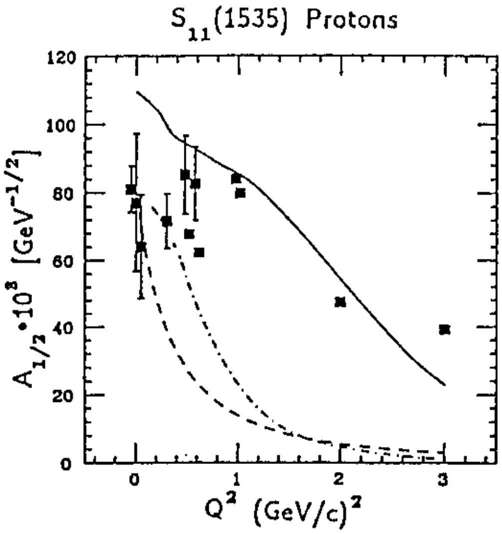



Fig. 4 The transverse helicity amplitude $A_{1/2}$ for $\gamma_v p \to S_{11}(1535)$ extracted from $\eta$ photo- and electroproduction data. The first 3 data points represent the result of 3 independent analyses of photoproduction data. The electroproduction data are from Bonn, DESY, and NINA[2,3,4,6].

The channel $\gamma_v N \to N'\pi$ contributes to both isospin 1/2 and 3/2. A detailed analysis of pion electroproduction therefore requires measurements in channels with different isospin content, e.g. $\gamma_v p \to p\pi^\circ$, $n\pi^+$ and $\gamma_v n \to \pi^- p$.

For some of the more prominent proton resonances as the $P_{33}(1232)$, $D_{13}(1520)$ and $F_{15}(1688)$, the transverse helicity amplitudes have been extracted from $p\pi^\circ$ and $\pi^+ n$ data for $Q^2$ up to $\simeq 3 (GeV/c)^2$[2,4,6].

The $P_{33}(1232)$ was found to be dominantly magnetic over the full $Q^2$ range, with the magnetic transition form factor dropping off faster with $Q^2$ than the elastic nucleon form factors (Fig. 5). Small contributions from the scalar and electric multipoles $S_{1+}$ and $E_{1+}$ have

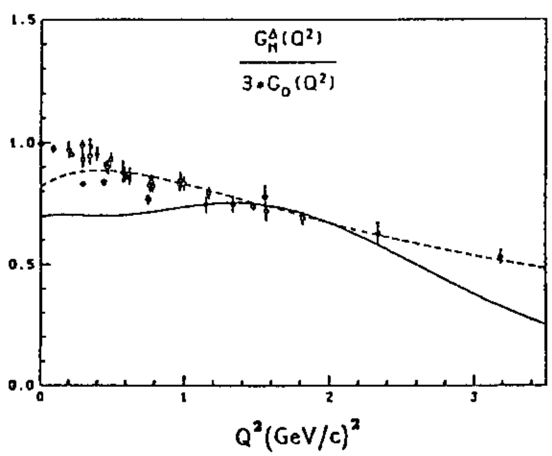



Fig. 5 The magnetic transition form factor $G_M^\Delta$ for $\gamma_v p \to \Delta(1232)$. The lines represent quark model calculations by Foster and Hughes[4] (dashed line) and Schroeder, Pfeil, Rollnik[5].

been measured with $\mathrm{Re}(S_{1+} \cdot M^*_{1+})/|M_{1+}|^2 \simeq 0.05$ to $0.1$ and $\mathrm{Re}(E_{1+} \cdot M^*_{1+})/|M_{1+}|^2 \simeq 0. - 0.05$ at $Q^2 \leq 1(\mathrm{GeV/c})^2$. At higher $Q^2$ the uncertainties in extracting these quantities are larger. A separation of resonant and nonresonant contributions in these quantities is difficult and would be considerably facilitated if the corresponding imaginary parts could be measured as well. Such a program requires detailed polarization experiments[6].

Precise measurements of the $S_{1+}$ and $E_{1+}$ multipoles are important as they allow testing of QCD ingredients in dynamical quark models. SU(6) quark models yield $S_{1+} = E_{1+} \equiv 0$. QCD quark models predict nonzero scalar and electric multipoles[7]. Pertubative QCD demands $E_{1+}/M_{1+} \to 1.$ for $Q^2 \to \infty$ [8].

The only other resonances which have been studied over an extended $Q^2$ range are the $D_{13}(1520)$ and the $F_{15}(1688)$. A common feature of both states is the switch from helicity 3/2 dominance at $Q^2$=0 to helicity 1/2 dominance at modestly high $Q^2$ (Fig. 6). This behavior is qualitatively, though not quantitatively, understood in the context of dynamical quark models, and appears directly related to the asymptotic behavior at large $Q^2$ (helicity conservation in $\gamma_v$-quark scattering). Perturbative QCD also predicts $A(Q^2 \to \infty) = 1$ for the

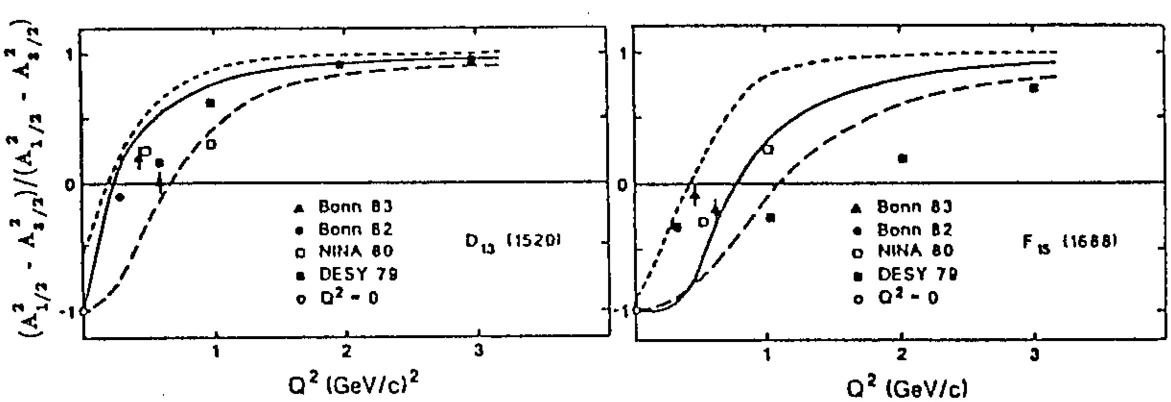



Fig. 6 Helicity asymmetries for the transition $\gamma_v p \to D_{13}(1520)$ and $\gamma_v p \to F_{15}(1688)$. The lines represent quark model calculations.

helicity asymmetry[8]. For the $P_{33}(1232)$ this helicity switch is not observed -- both components behave quite similarly with $Q^2$. For a pure magnetic resonance with unnatural parity the helicity 3/2 and 1/2 amplitudes are strictly related as $|A_{1/2}|^2/|A_{3/2}|^2 = (2J-1)/(2J+3)$. For the $P_{33}(1232)$ this leads to a helicity asymmetry $A = -1/2$. Only additional electric multipole contribution can yield a deviation from this value.

Little information from the analyses of electron scattering experiments is available for the other resonances, and virtually no information exists for neutron resonances.

## I.2 Nucleon Resonance Production at CW Electron Machines

Experimental programs at future CW machines should clearly include a broad program to measure the transition form factors of the relevant resonances. Precise measurements of the prominent resonances like $P_{33}(1232)$, $S_{11}(1535)$, $D_{13}(1520)$, $F_{15}(16\ 88)$ over a large $Q^2$ range are of paramount importance for testing QCD aspects of dynamical quark models[9]. Electroproduction of pions could also help solve the puzzle whether or not the Roper $P_{11}(1440)$ consists of two $P_{11}$ resonances, as a recent analysis of $\pi N$ scattering suggests[11]. The analysis of this particular mass region is complicated by the overwhelming dominance of the $P_{33}(1232)$ both in $\pi N$ and in $\gamma N$ scattering. In electroproduction, however, variation of $Q^2$ to some extent allows the enhancement or suppression of certain resonances relative to others. For example, the fast decrease of the $P_{33}(1232)$ excitation with $Q^2$ should enable a study of the Roper mass region at high $Q^2$ with little interference from the $P_{33}(1232)$.

In order to collect the experimental data for a model independent extraction of the pion production amplitudes, a systematic coverage of a large mass range at a given $Q^2$ is essential. Also, use of polarized electron beams, polarized nucleon targets, and measurements of recoil polarization asymmetries will be important and should be feasible considering, for example, recent advances in polarized target technology[10]. For many measurements involving polarization it will be necessary to provide sufficient capability for measuring hadrons out of the electron scattering plane.

## II. ELECTROMAGNETIC EXCITATION OF NUCLEON RESONANCES IN NUCLEI

Why do we want to study the behavior of resonances in nuclei? Nucleon resonances, isolated from nonresonant channels and from final state interaction, allow us to study the $\gamma NN^*$ vertex in nuclei and to search for possible modifications due to the nuclear environment. If, for example, the nucleon changes its size in the nuclear medium, one should expect to observe changes of the excitation spectrum and of the $Q^2$ dependence of the transition form factors. Another interesting aspect is the interaction of resonances in the nuclear medium. Models like the Δ-hole model, which have been very successful in describing Δ-nuclei interactions in pion scattering, can be tested in electron scattering. At large $Q^2$ excited states are produced with high momenta and may therefore be used as a means for studying incoherent ΔN and N*N scattering in nuclei. Finally, nucleon resonances may be of importance in the search for 'exotic' quark-gluon components, e.g. 6-quark clusters, which have been discussed extensively in the literature in recent years[12].

Electromagnetic probes appear particularly suited for studies involving nuclei, as they allow illumination of the entire nuclear volume uniformly. Another advantage is that elastic pion rescattering effects, which lead to strong resonance distortion in pion-nucleus scattering, are largely suppressed in the transverse coupling of photons[13].

### II.1 Total Photoabsorption from Nuclei

Global information on resonance parameters as excitation strengths, masses and widths is obtained from measurements of the total photoabsorption cross section with real and virtual photons. Fig. 7 displays the absorption cross section per nucleon for real

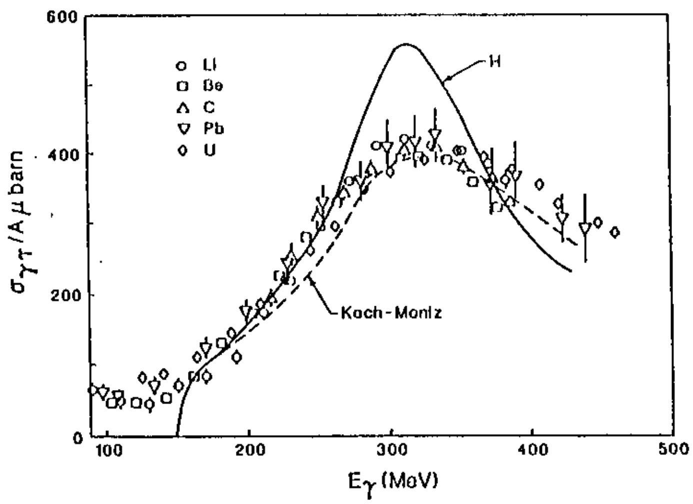



Fig. 7 Total photoabsorption cross section in the $\Delta(1232)$ region. The dashed line represents a calculation based on the $\Delta$-hole model[14].

photons, at photon energies in the $\Delta(1232)$ region. The first observation is that the $\Delta(1232)$ is strongly excited in nuclei by real photons. This is not surprising since we know from other reactions like (e,e′p) that nuclei consist to a very high degree of nucleons. The more surprising result is that the data appear to fall on a universal curve, at the present level of accuracy of the measurements. There is no obvious shift of the peak position compared to $\Delta$-production from free nucleons. The $\Delta$-hole model calculations by Koch & Moniz[14] account for the absolute cross section and slope near and above the maximum. This implies that there is no anomalous reduction of the $\Delta$ excitation strength, and conventional nuclear theory accounts for the gross features of the data. Discrepancies at the 20% level occur only at the low energy side of the resonance.

For some light nuclei $^4$He, $^9$Be, $^{12}$C and $^{16}$O inclusive electron scattering experiments have been performed at Bates[15]. Figure 8 displays the result of a fit to the experimental data. The cross section scales roughly with A in the vicinity of the $\Delta$ peak but is about 20% lower than for the free $\Delta$. The location of the fitted peak appears shifted by about 10 MeV to lower energies compared to free nucleons. It would, however, be premature to attribute this effect to a genuine shift of the Δ resonance peak. Other, nonresonant contributions at the lower energy side would also tend to shift the peak position into this direction. For $^{16}O$ the measurements are compared to Δ-hole model calculations by in Fig. 9. The calculations indicate a slight A dependence (not shown) which is consistent with the data. Near the Δ peak the data are qualitatively described, whereas at lower energy losses, the notorious discrepancy in the 'dip region' persists.

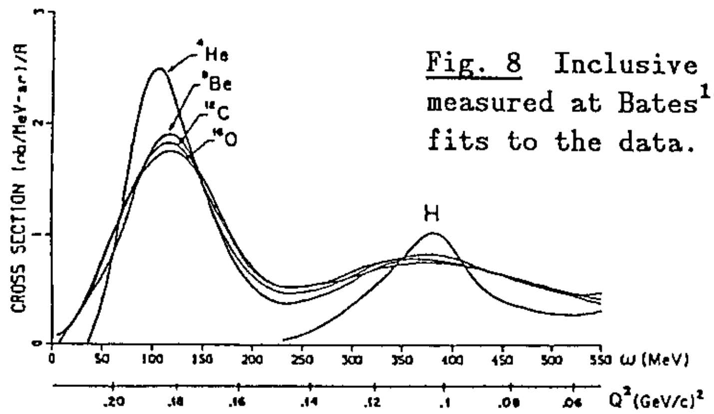



Fig. 8 Inclusive electron scattering data measured at Bates[15]. The lines represent fits to the data.

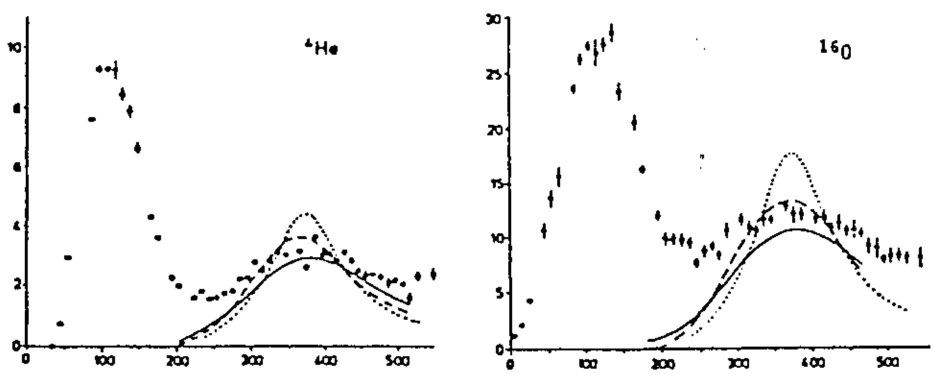



Fig. 9 Inclusive electron scattering data for $^{16}O$ from Bates[14] compared to Δ-hole model calculations by Koch and Ohtsuka[15] (solid line).

Inclusive electron scattering from $^{6}Li$ and $^{12}C$ measured at DESY have been analyzed to extract information on the total photoabsorption cross section of the Δ(1232) in nuclei[17].

Fig. 10 shows the ratio of the Δ cross section in the nucleus divided by the free nucleon cross section. A strong quenching is observed in this analysis, in the $Q^2$ range from 0.2 to 0.4 $(\mathrm{GeV/c})^2$. Another group reanalyzed the same data using a different technique and found no quenching[18]. To obtain information on the excitation strength of resonances in nuclei, which is subject to fewer systematic uncertainties, detailed exclusive experiments are necessary, where the final state hadrons are detected in coincidence with the scattered electron[19].

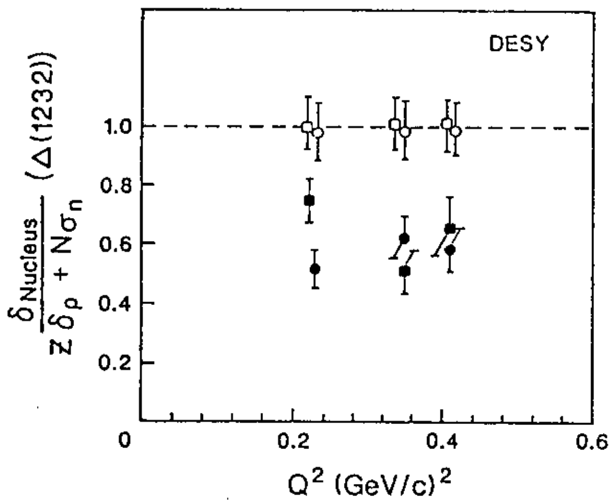



Fig. 10 Ratio of Δ(1232) production in $^6$Li (circles), $^{12}$C (squares) and from free nucleons. Two independent analyses of the same data are shown.

II.2 Total Pion Photoproduction from Nuclei

More exclusive measurements on nuclei in the Δ region have been done primarily with real photons. Total cross sections for $\pi^{\pm}$ and $\pi^{\circ}$ photoproduction have been measured. Fig. 11 shows recent data of total $\pi^{\circ}$ production measured at Bonn[20]. The Δ peak is visibly broader than in the total photoabsorption cross section and rather flat, at least for the heavier nuclei. The production cross section does not scale with A as the total absorption cross section does.

It is interesting to compare $\sigma(\gamma,\pi)$ with $\sigma(\gamma,\mathrm{hadron})$ for different values of A. This is shown in Fig. 12 at a photon energy near the Δ peak. $\sigma(\gamma,\pi^{\pm})$ exhibits the same A dependence as $\sigma(\gamma,\pi^{\circ})$, within the systematic errors of the measurement.

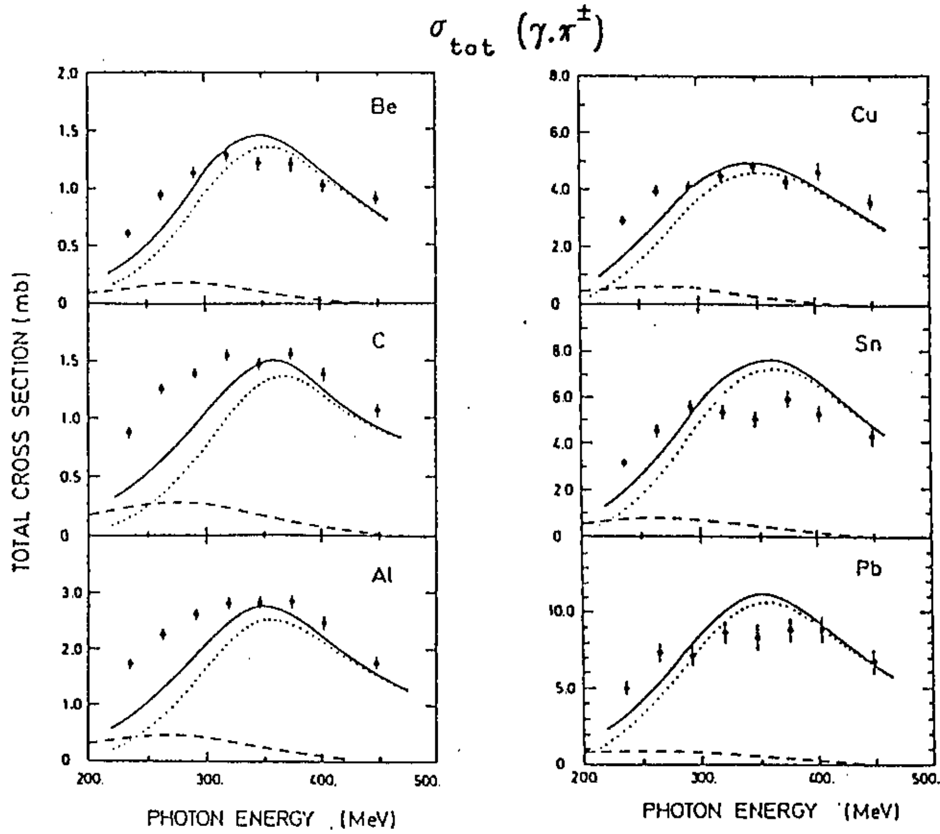



Fig. 11 Total $\pi^{\circ}$ photoproduction cross section in the $\Delta(1232)$ region. The solid lines represent the results of a simple cascade model.

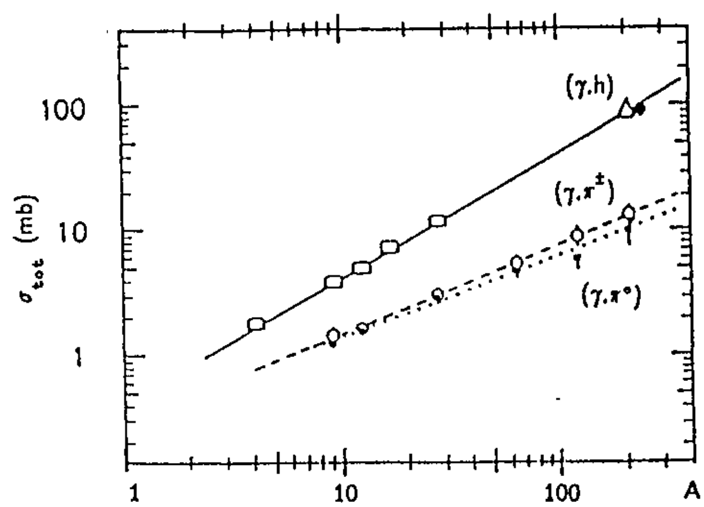



Fig. 12 Comparison of the total hadronic, $\pi^{\circ}$, and $\pi^{\pm}$ photoproduction cross section near the maximum of the $\Delta$ peak. Data from Bonn[20].

At large A values $\sigma(\gamma,\pi)$ accounts only for a fraction of $\sigma(\gamma,h)$ the total hadronic production. For uranium this fraction is only 30%. The remaining part has to be accounted for by the emission of nucleons. The data can be fitted with a simple exponential A dependence $\sigma \simeq A^{\alpha}$.

Both $\pi^{\circ}$ and $\pi^{\pm}$ production exhibit a $\sigma(\gamma,\pi) \simeq A^{2/3}$ dependence (Fig. 13) which is characteristic for particle production at the surface of the nucleus. This result is still consistent with resonance production over the entire nuclear volume if final state interaction and pion absorption effects are taken into account. These results confirm experiments in $\pi$-nucleus scattering, which demonstrated that nuclei are "black" to pions in the energy range of $\Delta$ production[22].

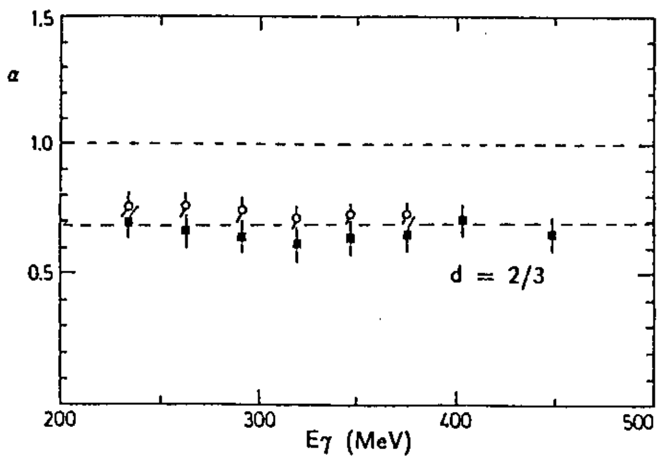



Fig. 13 Results of a fit with $\sigma(\pi) \sim A^{\alpha(E)}$ to the data in Fig. 12[20]

In the following I want to discuss experiments which may shed some light on the interaction of $\Delta$'s in nuclei. From the experiments discussed above it is clear that $\Delta$'s are produced over the entire nuclear volume, but only $\Delta$'s produced near the surface contribute to the pion yield. $\Delta$'s produced in the interior therefore must transfer their energy to other nucleons. This process involves at least two nucleons, in the simplest case $\Delta N \to NN$ (Fig. 14). Reactions like (e,e′pp) and (e,e′pn) should therefore be sensitive to $\Delta$ interaction in nuclei.

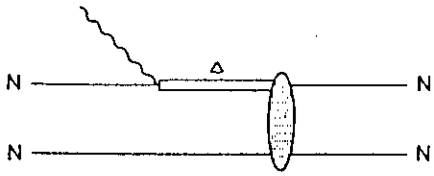



Fig. 14 Non-pionic Δ(1232) de-excitation mechanism in nuclei involving two nucleons.

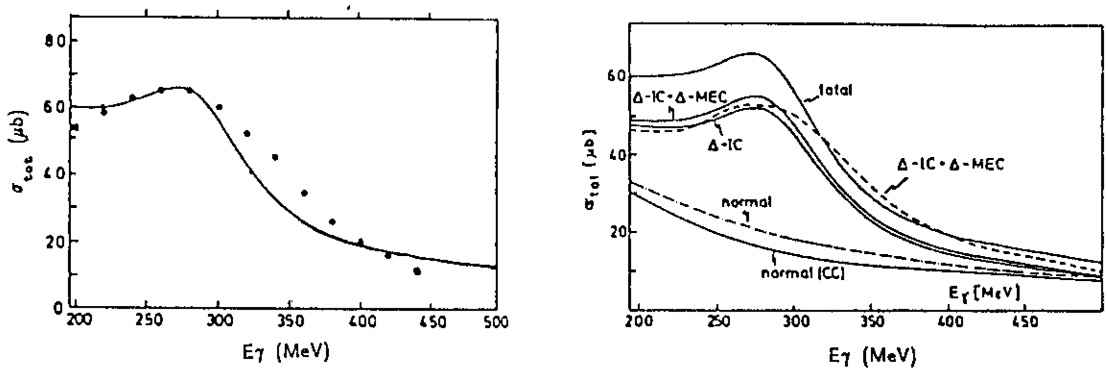



Fig. 15 Left: Total cross section for deuteron photodisintegration in the Δ(1232) region. Data from Bonn[23]. Non-relativistic calculations from Leidemann and Arenhoevel[24]. Right: Contributions to the total cross section (normal = nucleon + meson exchange currents).

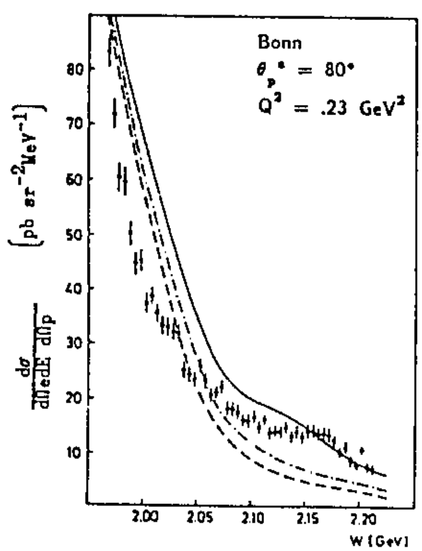
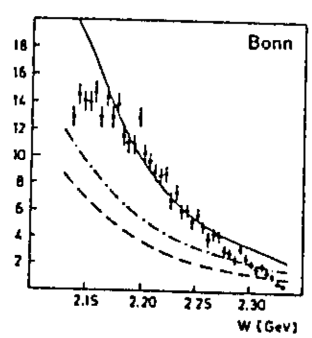



Fig. 16 Differential cross section for electrodisintegration of deuterons. Data from Bonn[25]. Non-relativistic calculations by Leidemann and Arenhoevel[24].



## II.3 The Reactions d(γ,p)n and d(e,e′p) in the Δ(1232) Region

Photo- and electrodisintegration of the deuteron in the Δ energy region is the simplest process which should be sensitive to ΔN interaction. Photodisintegration in the Δ region has been measured at various laboratories, however with large systematic discrepancies of up to 50%. The most recent measurement from Bonn[23] used a tagged photon beam and should be subject to smaller systematic uncertainties. The total cross section, displayed in Fig. 15, shows a pronounced enhancement that has been associated with the Δ(1232). Theoretical calculations[24] are able to reproduce the general features, although they fail to reproduce the details. Δ isobar currents clearly dominate the cross section over a large part of the Δ energy range.

Electrodisintegration of deuterons allows us to study various contributions to the coincidence cross section.

$$\frac{d\sigma}{d\Omega_o dE' d\Omega p} = \Gamma_T\left(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi\ \sigma_{TT} + \sqrt{\epsilon(\epsilon+1)/2}\ \cos\phi\ \sigma_{TL}\right)$$

The Δ isobar current is expected to contribute mainly to $\sigma_T$. By varying $Q^2$ one can probe the process at different distances. The first electrodisintegration measurements that completely covered the Δ mass region were recently carried out at the Bonn 2.5 GeV. No attempt, however, was made to separate the various terms in the cross section. The data are plotted in Fig. 16 as a function of the invariant mass of the final state p-n systems. A clear enhancement near the NΔ threshold emerges.

The comparison with the calculation based on non-relativistic theory[24] again emphasizes the importance of Δ-isobar currents in the disintegration process.

A comparison of the photo- and electrodisintegration measurement is shown in Fig. 17. The drop in cross section is largely explained by the $Q^2$ dependence of the nucleon form factors. The different shape of the cross section may partly be due to the longitudinal contribution in the electron data, which have not been separated off.

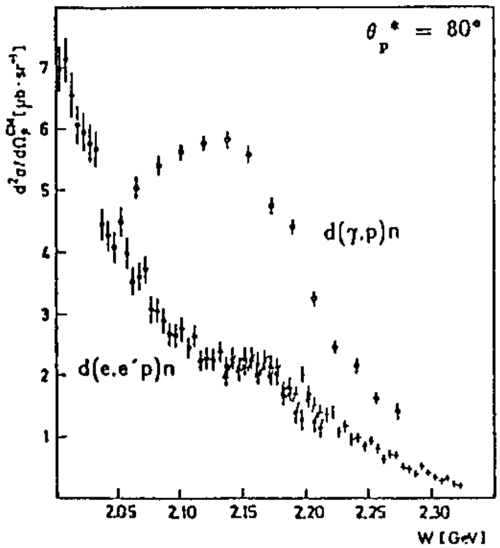



Fig. 17 Comparison of deuteron photo- and electrodisintegration in the Δ(1232) region.

It would be very interesting to extend these measurements to higher $Q^2$ and to higher excitation energies to probe both the short-distance behavior of the deuteron wave function and the role played by the higher nucleon resonances.

## II.4 The Reaction A(γ,p)X in the Δ-Region

The (γ,p) reaction was used by S. Homma et al.[26] to investigate quasifree pion production and nucleon-nucleon correlation for light nuclei in the Δ-region, using a tagged photon beam. Momentum distributions of the outgoing proton were measured at a fixed proton scattering angle of $\theta_p = 30°$. The data are displayed in Fig. 18 and show a structure that is interpreted as being the result of a superposition of two basic reactions, pion production from quasifree nucleons and photodisintegration of a quasi two-nucleon system.

This interpretation is motivated by the results on deuterium where the two enhancements in the spectrum can easily be associated with the respective two reactions. A fit to the data with a superposition of two Gaussian distributions is used to extract the cross section for the respective reactions. The quasifree two-nucleon disintegration data exhibit a shape which is rather similar to the photodisintegration data. This feature hints at the importance of Δ excitation in this reaction for light nuclei.

The "quasifree" pion production cross section shows a behavior which is quite different from the free nucleon case. The maximum of the peak appears to be shifted to higher excitation energies with increasing nucleon number.

A word of caution may, however, be in order in interpreting these data. The lower photon energy data require large corrections due to the unmeasured part of the proton spectrum ($p < 300$ MeV/c). It is not obvious from the data that the hypothesis of a Gaussian distribution applies to the lower momentum part of the distribution. Therefore, in particular, the cross section at lower photon energies may be subject to sizeable systematic uncertainties.

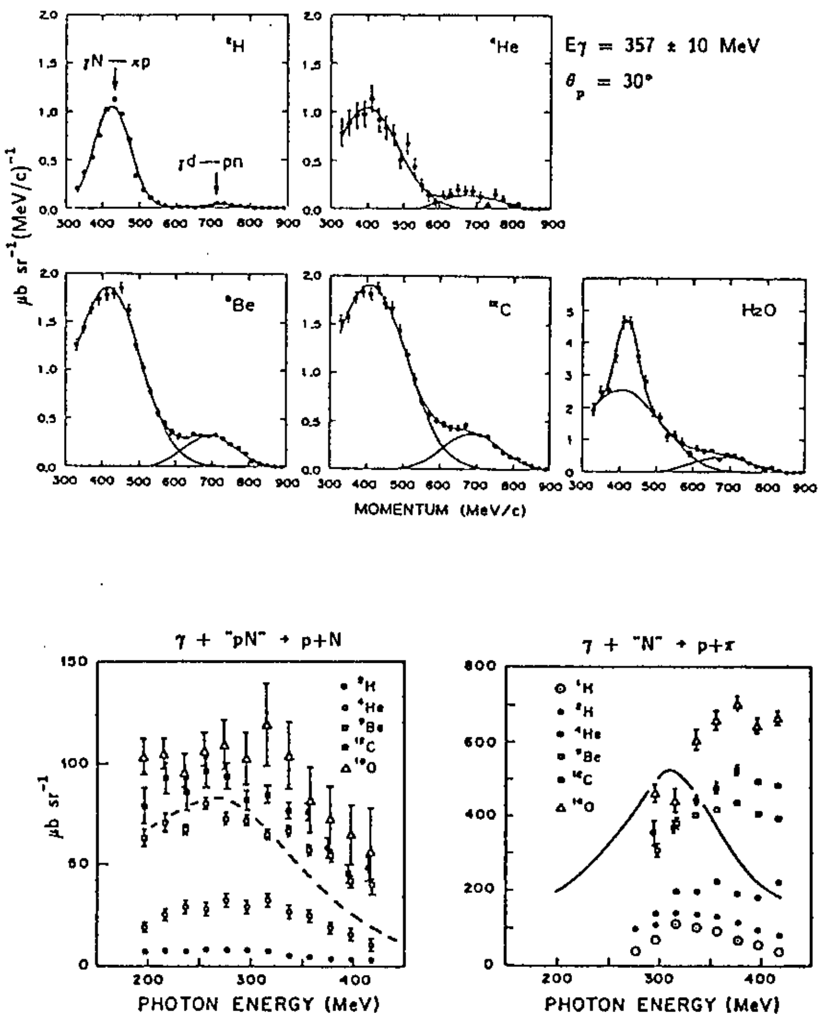



Fig. 18 Top: Momentum spectra of protons emitted in $(\gamma,p)$ reactions. Bottom: Total cross section of quasifree two-nucleon disintegration (l.h.s.), and quasifree pion production (r.h.s.) in the $\Delta(1232)$ region. Data from Tokyo[26].

II.5 $\Delta(1232)$ Propagation and Nuclear Structure

An interesting aspect of $\Delta$ interaction in nuclei is the interplay of $\Delta$ propagation and the specific nuclear structure. Reactions of the type ${}^{z}A(\gamma,\pi^{\pm})^{z\pm1}A$, where the final nucleus remains in a well-defined state, have been studied at MIT-Bates and at NIKHEF.

The reaction ${}^{14}N(\gamma,\pi^{+})^{14}C_{gs}$, which corresponds to a $(J^P, I) = (1^+, 0) \to (0^+, 1)$ transition, is expected to enhance effects of the $\Delta$ excitation. From $\beta$-decay it is known that A=14 nuclei have small Gamov-Teller strengths implying a reduced Kroll-Ruderman term ~ $(\vec{\sigma}\cdot\vec{\epsilon})$ which, at lower energies, is responsible for a large fraction of the nonresonant transition. In Fig. 19 angular distributions are shown for two incident photon energies below and near the maximum of the $\Delta(1232)$ resonance.

A resonant structure clearly emerges, but is well accounted for by the theoretical calculations only in the lower energy region. Calculations by R. Wittman and N. Mukhopadyay[27] use an improved description of the elementary process in the resonance region and near threshold, and implement unitarity. The pion final state interaction is treated in the $\Delta$-hole approach. A very recent calculation, presented by D. Drechsel at this conference, gives a better account of the data at higher energies[29].

The process ${}^{13}C(\gamma,\pi^{-})^{13}N_{gs}$, which corresponds to a p-shell transition, has been studied at Bates[30]. In a nonrelativistic description, the nonresonant production is expected to be dominantly spin dependent ~ $(\vec{\sigma}\cdot\vec{\epsilon})$ and described by the nuclear multipole M1, whereas the resonant production is spin-independent ~ $\vec{\epsilon}\cdot(\vec{k}_\gamma \times \vec{q}_\pi)$ and should proceed via the coulomb multipole C0. Near the minimum, in the ${}^{13}C$-M1 form factor which appears at $|\vec{k}_\gamma - \vec{q}_\pi| \simeq 1\mathrm{fm}^{-1}$, the nonresonant production is expected to be largely suppressed.

Data from NIKHEF[31] are shown in Fig. 20 for momentum transfers near the minimum and near the first maximum of the M1 form factor. Resonance contributions from the $\Delta$ are not observed to the extent they are predicted by the theoretical calculations. The resonant production is considerably overestimated, which hints at a not-well-described $\Delta$-nucleus dynamics. Also, the nonresonant part is poorly described at higher photon energies.

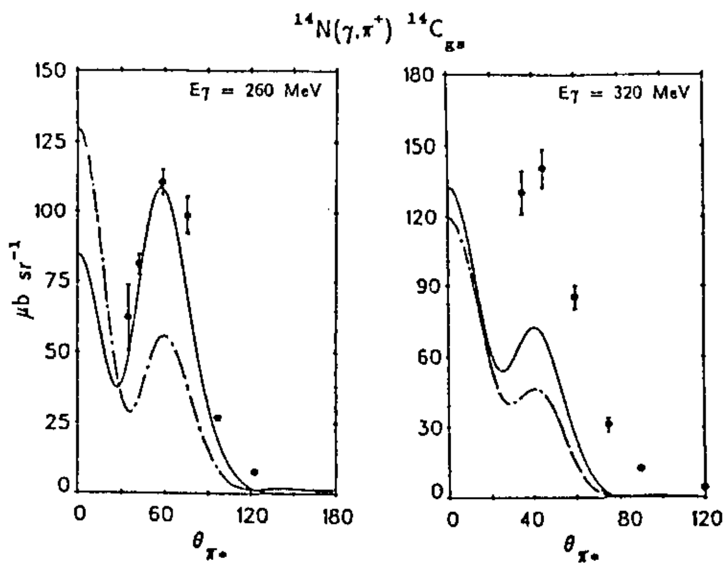



Fig. 19 Angular distributions of pions from the reaction $^{14}N(\gamma,\pi^+)^{14}C_{gs}$. Data from Bates[30]. Theoretical calculations by R. Wittman and N. Mukhopadyay (solid line)[27] and L. Tiator and L.E. Wright[28].

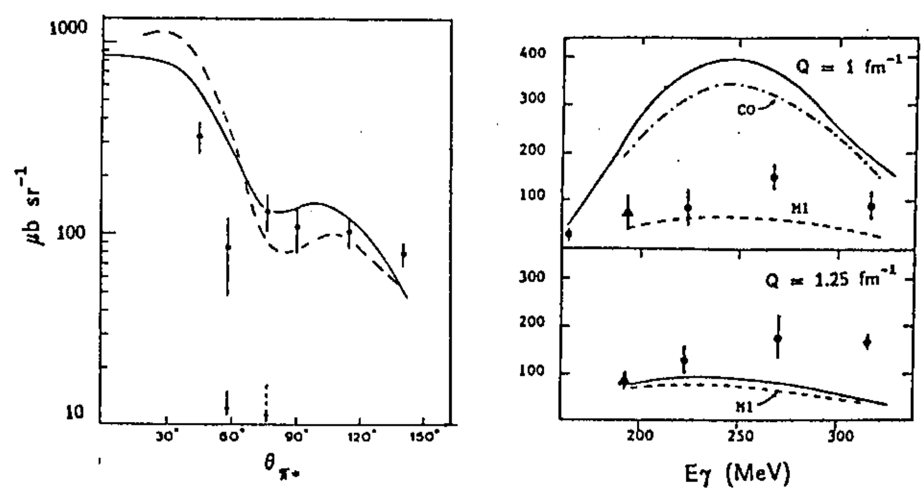



Fig. 20 Angular distribution and excitation spectra in the reaction $^{13}C(\gamma,\pi^-)^{13}N_{gs}$. Data from NIKHEF[31]. Lines represent DWIA calculations.

Coherent $\pi^\circ$ production data in the reaction $^4He(\gamma,\pi^\circ)^4He$ from MIT-Bates[23] are shown in Fig. 21. The data are well described by Δ-hole model calculations. The authors, however, point out that the shape of the curve is largely constrained by model-independent factors. At 0°, coherent $\pi^\circ$ production from a spin 0 nucleus must vanish due to angular momentum conservation, and at large angles the cross section must fall off due to the nuclear form factors.

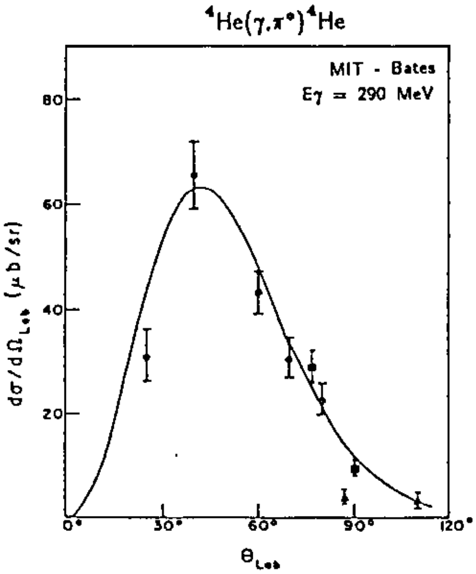



Fig. 21 Angular distribution of coherent $\pi^\circ$ production in $^4He(\gamma,\pi^\circ)^4He$ near the maximum of the Δ(1232). Data from Bates[32].

## II.6 Pre-existing Isobar Components in Nuclei

Predictions of the existence of isobar components in the deuteron wave function at the one percent level[23] prompted an intense experimental search for these objects in the mid 1970's, with inconclusive results (table). Since the deuteron has isospin I = 0, only pairs of $\Delta^{++}\Delta^-$ and $\Delta^+\Delta^\circ$ can contribute. More recent predictions of the ΔΔ probability relative to the NN probability are in the range of $\simeq (1\text{-}5)10^{-3}$. Early experiments did not reach the level of accuracy to test such small ΔΔ components.

In a recent experiment[34] the reaction $\nu d \to \mu^- n\Delta^{++}(\Delta^{++} \to p\pi^+)$ was studied. A spectator $\Delta^{++}$ would show up at low momenta of the $p\pi^+$ pair, whereas directly produced $\Delta^{++}$ would occur at large momenta. The data are displayed in Fig. 22. The high momentum bin contains a large $\Delta^{++}$ component, whereas the low momentum bin is consistent with no $\Delta^{++}$ contribution, yielding an upper limit of 0.2% (90% c.L.) for the ΔΔ components. This limit comes close to seriously constraining the theoretical predictions. There are, however, uncertainties in the interpretation which have to be settled. For example, it is not obvious that the naive spectator picture is applicable for such a deeply bound system as the ΔΔ. It is also not obvious that the spectator Δ remains intact in an interaction where it has to pick up an energy of ≃ 300 MeV to reach the mass shell.

The difficulties of these experiments and their interpretations are also related to the smallness of the expected effect. In heavier nuclei one may expect an appreciably larger Δ content[35].

| REACTION | $I_{\Delta\Delta}/I_{NN}$ | |
|---|---|---|
| $\bar{p}d \to p_s \bar{p} p \pi^-$<br>$\to \bar{p}_s p p \pi^- \pi^0$ | ~ 16% | H. Braun (1974) |
| $nd \to n\pi^+\pi^- pn$ | < .7% | C.P. Horne (1974) |
| $\gamma d \to \Delta^{++}X$ | ~ 3% | P. Benz, P. Soding (1974) |
| $\pi^+ d \to p_s p \pi^+ \pi^- \pi^0$ | < .8% | M.J. Emms (1974) |
| $dp \to nnp\pi^+$<br>$\to ppn\pi^0$<br>$\to ppp\pi^-$ | < (1.1 ± 0.3)% | B.S. Aladashvili (1975) |
| $\pi^- d \to p\Delta^-$ | < .4% | R. Beurtey (1976) |
| $pd \to p_s pp\pi^-$<br>$\to p_s pp\pi^-\pi^0$ | 0.1 ± 0.2% | V. Bakken (1979) |
| $\nu d \to \mu^- n\Delta^{++}$ | < .2% (90% c.l.) | D. Allasia (1986) |

$\nu d \to \mu^- n\, \Delta^{++}$

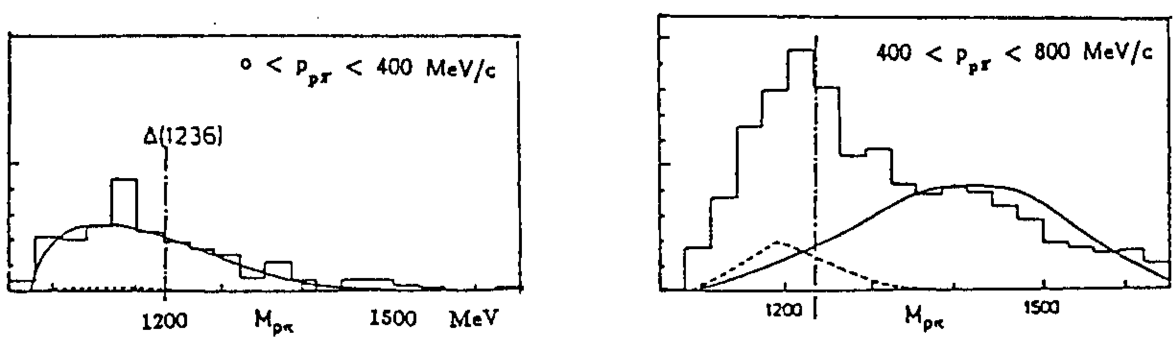



Fig. 22 Invariant mass distribution of $p\pi^+$ pairs in the reaction $\nu d \to \mu^- np\pi^+$ for $0 < p_{p\pi} < 400$ MeV/c (left) and $400 < p_{p\pi} < 800$ MeV/c (right).

Recently, H. Lipkin and T.S. Lee[36] studied effects of preexisting $\Delta$-isobars in $^3$He. They found that under certain kinematical conditions, measurements of the $\pi^+/\pi^-$ ratio in $(e,e'\pi)$ as well as triple coincidence measurements $(e,e'\pi N)$ should be very sensitive to even small probabilities of finding a $\Delta$ in $^3$He.

## III. NUCLEON RESONANCES IN NUCLEI -- FUTURE PROSPECTS

At future CW electron machines with energies well in excess of 1 GeV and with high electron currents, experiments in the resonance region requiring double and triple coincidence measurements will become feasible. Also, the use of large acceptance spectrometers with open geometries opens up the possibility of studying properties of nucleon resonances and their interaction in nuclei in exclusive measurements.

Among the many intriguing aspects, I want to briefly address only two: the study of modification of the $\gamma NN^*$ vertex and the $\Delta$ and $N^*$ interaction at high momentum transfer.

Modifications of the $\gamma NN^*$ vertex may result in changes of the excitation energies, the excitation strengths and their $Q^2$ dependence. These effects are presumably small, and multipole analyses of comparable quality as for free nucleons will be needed for a detailed comparison. Such a program requires measuring the complete final state in order to preserve the exclusiveness of the process.

The most promising reactions to isolate single resonances are $\pi^\circ$ production in the $\Delta(1232)$ region and $\eta$-production in the region of the $N^*(1535)$. $\pi^\circ$ production near the $\Delta$ proceeds predominantly through the resonant channel with little background at not too large $Q^2$. Charged pion production is less favorable in this respect as the pion pole term gives sizeable nonresonant contributions. For $\eta$ production in the $N^*(1535)$ region the situation is even more favorable. The $N^*(1535)$ has a large branching ratio into the $\eta$ channel ($\simeq$ 50%). The $N^*(1520)$ which is nearby has a very small branching ratio into this channel ($\simeq$ 0.1%). Angular distribution of $\eta$ production exhibits an almost pure s-wave structure and the invariant mass distribution shows a resonant behavior with little nonresonant background (Fig. 3).

In both cases, a single multipole dominates the resonant cross section, the $M_{1+}$ for the $\Delta(1232)$ and the $E_{0+}$ for the $N^*(1535)$, which simplifies the analysis considerably. Clearly the detection of $\pi^\circ$ and $\eta$ at high luminosities, both through their $2\gamma$ decays, with sufficient resolution provides an experimental challenge.

To minimize final state interaction of the outgoing $\pi^\circ$ and $\eta$ the kinematics can be chosen such that subsequent absorption of the emitted mesons due to resonance production is unlikely. This can be accomplished by going to high $Q^2$. Fig. 23 displays the situation for $Q^2$=0 and $Q^2$=2(GeV/c)$^2$. At $Q^2$=0 pions and etas are produced under kinematical conditions that favor reabsorption due to subsequent resonance production in $\pi$N and $\eta$N scattering. At $Q^2$=2(GeV/c)$^2$ reabsorption should be largely reduced in $\pi$ production and almost completely absent in $\eta$ production. Also, the $\eta$N coupling constant has been found substantially smaller than $\pi$N coupling[37] which further reduces the $\eta$ reabsorption probability in nuclei.

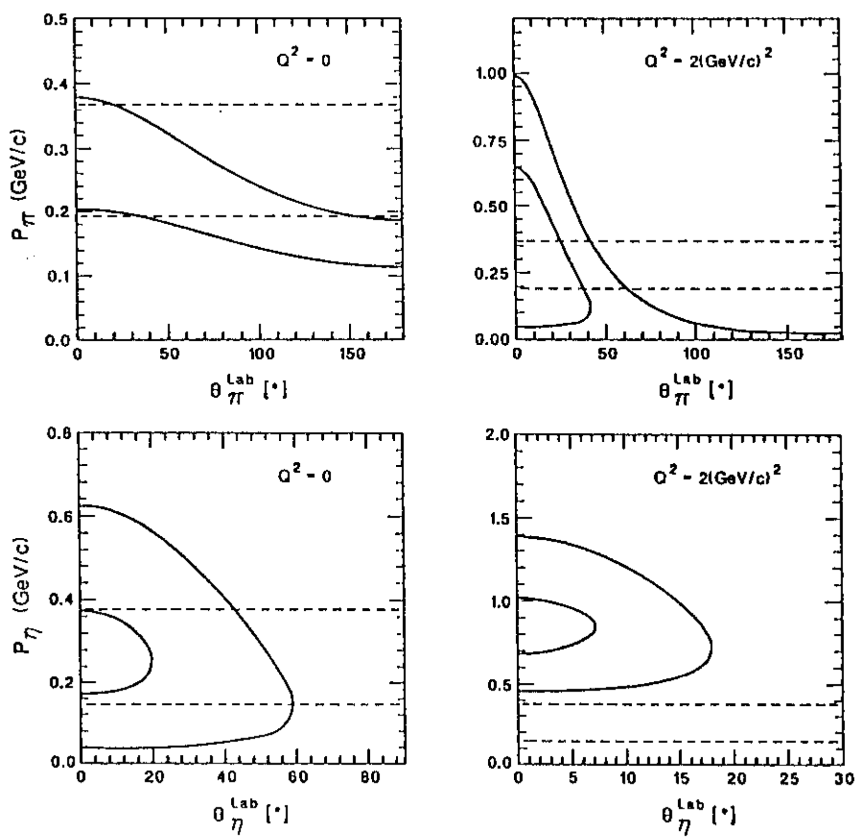



Fig. 23 Photo- and electroproduction kinematics for $\gamma p \to \pi N$ and $\gamma p \to \eta N$ in the region of the $\Delta(1232)$ (top), the $N^*(1535)$ (bottom), respectively. The dashed lines indicate the pion and eta momentum ranges where resonance absorption for $\pi N \to \Delta(1232)$ and $\eta N \to N^*(1535)$ is expected to be large.

The production of nucleon resonances at high $Q^2$ results in resonances traversing the nuclear medium with large momenta. The mean flight path before decay increases with $Q^2$ and may become large compared to the mean distance between nucleons in nuclei. In free production the $\Delta(1232)$ remains a prominent resonance up to $\simeq 4$ $(GeV/c)^2$, and the $N^*(1535)$ appears to remain the dominant resonance up to the highest $Q^2 \simeq 6$ $(GeV/c)^2$ which have been achieved so far.

A comparison of $\Delta(1232)$-N and $N^*(1535)$-N scattering at high energies may reveal effects due to the different spin and isospin. Possible differences of the physical extensions of the $\Delta(1232)$ and $N^*(1535)$, as indicated by the different $Q^2$ dependence of their respective transition form factors, can be studied as well.

As resonances in nuclei can be produced with variable momenta, one may also employ this technique in the search for dibaryon resonances. Dibaryon states are produced in NN collisions with high inelasticity, which means that they are unlikely to be seen in $NN \rightarrow NN$ scattering but may have much larger production probabilities in $\Delta N \rightarrow \Delta N$ or $\Delta N \rightarrow \Delta\Delta$. Needless to say, these reactions can only be studied in nuclei.

It has been speculated that there are sizeable multiquark components pre-existing in nuclei[38]. If this is the case, these states can certainly be excited in electron scattering and are likely to decay into channels containing resonances in the final states[35].

$$\gamma_v (6Q)_v \rightarrow (6Q)^* \rightarrow N\Delta,\ \Delta\Delta,\ NN^*$$

Experiments searching for final state nucleon resonances with the transverse momentum (with respect to $\gamma_v$) roughly balanced by a nucleon or another resonance should be quite sensitive to such multiquark configurations. Clearly, measurements of this type require experimental equipment with very large acceptances, for example of the type described by B. Mecking[39] at this Workshop.

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